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Developing an Optical Testing Method for Space Telescopes

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Next Generation Space Telescope (NGST) is under design study for proposed launch around 2008. It will take over the task of Hubble Space Telescope (HST) and provide much more detailed information about celestial objects.

Present large telescopes both in space and on the ground contain aspheric mirrors, called Ritchey-Chrétien type. As the size of the telescope becomes larger and the optical quality is requested to be higher, reaching the diffraction limit, more accurate optical testing methods are required. However, there are few testing methods which can achieve the required accuracy for aspheric optics, and none of them has achieved it with certainty. The failure of producing the primary mirror of the Hubble Space Telescope to meet specification is a good example. Moreover, testing aspheric mirrors of large convex form adds the difficulty to extreme.

In this paper, space telescopes and large ground-based telescopes are surveyed and testing methods for aspheric optics are reviewed. A method of testing aspheric convex mirrors is suggested.

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I. INTRODUCTION

Numerous space telescopes are orbiting the Earth or stepping their way forward to dark space, sending back vast amounts of information about our surroundings. Among them, the Hubble Space Telescopes is one of the most distinctive and well-known space telescope. Though it had initially failed to achieve the required optical quality, it provides valuable information to astronomers after repair.

The mission of HST is expected to end in 2010. In order to continue the scientific work of HST and to investigate nature in further detail, the Next Generation Space Telescope (NGST) project was launched. The design study of NGST is being performed mainly by Space Telescope Science Institute (STScI). The size of NGST will be much larger than HST. Whereas the diameter of HST is 2.4m, that of NGST would be 8m which is similar to the size of large telescopes on the ground. Therefore, the techniques and know-how of building large telescopes can be transported to the development of NGST.

A dozen of ground-based large telescopes will be completely constructed within a few years. As for optical systems, most of them contain Ritchey-Chretien type (RC), which consists of a hyperbolic concave primary mirror and hyperbolic convex secondary mirror. This system enhances the image quality compared to other systems which consist of spherical and parabolic mirrors. However, one drawback of RC is that it has significant aspheric departure, which is extremely difficult to produce. The main difficulty is that there is no confirmed optical testing method to measure aspheric optics with high accuracy. Moreover, large telescopes request more and more highly accurate optics, reaching up to the diffraction limit. Without an appropriate testing method, the telescope cannot achieve the required accuracy. The initial failure of HST is a good example. In case of testing a large convex mirror, the difficulty is increased by a lack of testing tools. The importance of testing cannot be over emphasized.

In the next two sections, HST, NGST, and ground-based large telescopes are described. The importance of optical testing is emphasized in section 4 from the initial failure of HST and a problem of testing aspheric optics by using interferometry is analyzed in section 5, followed by various compensating test methods. Methods of testing large convex mirrors are suggested in section 6 and conclusions follow.

II. SPACE TELESCOPES - HST AND NGST

Hubble Space Telescope (HST) is the most distinctive space telescope at present. It provides lots of new

TABLE 1. Characteristics of space telescopes and large telescopes.

	HST	NGST	VLT	Gemini	Subaru	Keck
Telescopes	1	1	4	2	1	2
Diameter	2.4 m	8 m	8 m	8 m	8.3 m	10 m
Type	RC	N/A	RC	RC	RC	RC
f/# Primary	2.35	N/A	1.8	1.8	1.8	1.75
Conic const	-1.0139	N/A	-1.004616	-1.003756		
Image size[arcsec]	0.1 (θ_{70})	diffraction limit at 2μm	0.038 / 1.5 arcmin	0.1(θ_{50}) at 2.2μm	0.17 (θ_{50}) at 0.5μm	0.4 (θ_{80})
Remarks	launch 1990	launch 2008	Active optics	Adaptive optics	Active optics	Segmented primary

discoveries and detailed information of interesting celestial objects, which cannot be achieved from ground-based telescopes. Hubble Space Telescope was launched in 1990. HST is a 2.4m in diameter and f/24 RC system, with f/2.35 primary mirror. The mirror was made to give a diffraction-limited performance in the visible area, having the theoretical rms surface deviation of 1.3×10^{-8}m, which is equivalent to 0.02λ at the wavelength of 632.8nm.

Next Generation Space Telescope (NGST) [1] has been under study since 1995 and is planned to be launched around 2008, over 60 years after Lyman Spitzer proposed space telescopes. The mission is a logical successor to the HST, providing better understanding of the universe and our Solar system and finding Earth-like planets beyond our Solar system. NGST will be an 8m class telescope combined with segmented mirrors, and operating for 10 years near the Earth-Sun second Lagrange point (L2), 1.5 million km from Earth. It will have a relatively fast primary mirror to minimize telescope length. A deformable mirror is used for wavefront correction so that the system will be diffraction limited below 2μm. According to simulation of typical wavefront errors due to optical, mechanical, and thermal errors, the final image will have a Strehl ratio of about 81% at 2μm, and 60% at 0.6μm. Fig. 1 shows the design of NGST and Table 1 gives the characteristics of space telescopes and 8m class telescopes.

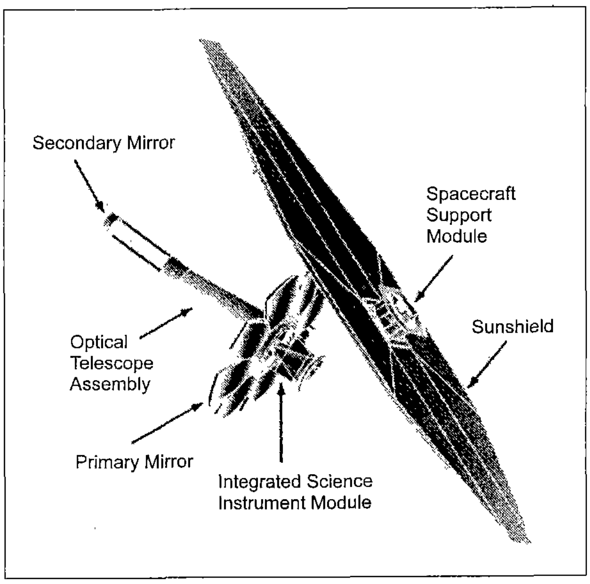

FIG. 1. Concept design of NGST.

III. GROUND-BASED LARGE TELESCOPES

Ground-based telescopes of 8m class are completed or being built. They are European Southern Observatory (ESO)'s four 8m Very Large Telescope (VLT), Gemini two 8m telescopes, Subaru 8.2m telescope, Keck 10m telescopes, etc. As ground-based telescopes precede the space telescope, it's worthwhile to review the up-to-date technology used on the ground telescopes.

ESO's VLT is an array of four 8m RC type telescopes which is being built in Chile. The primary mirrors are f/1.8, 177mm in thickness, and are controlled by active optics. The optical image quality is constantly checked by using a reference star and controls the form of the thin primary mirror to acquire the best image. The geometric image sizes will be 0.038 arcsec rms in the field radius of 1.5 arcmin. The optical surfaces of the primary mirrors of the first two telescopes had rms wavefront errors of 43nm and 38nm, respectively, in active mode.

The Gemini telescopes [2] are twin telescopes, which will be located on Hawaii and in Chile covering both north and south hemispheres by the almost identical telescopes. They are being made by an international partnership of the U.S.A., U.K., Canada, Chile, Argentina, and Brazil. Telescopes are RC type and 8m in diameter with f/1.8 primary mirror. The image size is pursued to be 0.1 arcsec in diameter which has 50% of encircled energy (θ_{50}) at 2.2μm, and surface roughness to be 2nm or better. Fig. 2 shows the expected image quality of the telescopes in several cases. They

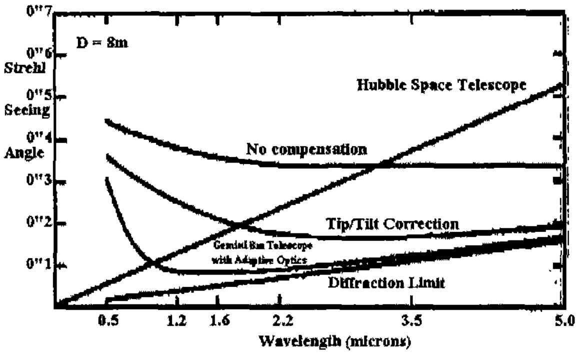

FIG. 2. Expected image quality of the Gemini telescopes [3].

are compared to the optical quality of HST and to the diffraction limit.

Subaru [4] is a 8.3m Japanese telescope, which is built at Mauna Kea, Hawaii. The focal ratio is f/1.8 for prime focus and the primary mirror is supported by active supporting structures. The expected image size is 0.17 arcsec at 0.5μm and 0.13arcsec at 1.0μm in the 50% encircled energy (θ_{50}) without air turbulence. The image quality of the primary mirror is hoped to be 0.1 arcsec at the wavelength of 0.5μm.

Keck I and II [5,6] are two 10m telescopes on Mauna Kea, Hawaii. The primary mirrors of Keck are f/1.75 hyperbolic mirrors, each consisting of 36 hexagonal segments. Both telescopes have the rms surface error of 40nm and image diameter of 0.4 arcsec in the 80% encircled energy.

Besides, 8.4m Large Binocular Telescope, Hobby-Eberly telescope with 9m segmented primary, 6.5m single mirror conversion of Multiple Mirror Telescope, and Magellan 6.5m are being built. About ten of 8-10m telescopes will be built by this decade.

IV. A PROBLEM IN HUBBLE SPACE TELESCOPE: PRIMARY MIRROR

Soon after HST was launched, it was found that the primary mirror was figured incorrectly. The telescope has spherical aberration due to incorrect conic constant from the designed value of -1.0023 to the presumed actual value of -1.0139±0.0003 (1σ), producing a flatter than intended mirror by -2.2μm at the edge [7,8].

The mistake came from the testing of the primary mirror. The test was undertaken in 1980-81 by a COaxial Reference Interferometer (CORI) with a Reflective Null Corrector (RNC) which consisted of a field lens and two spherical mirrors. The RNC was made to have the same spherical aberration as the primary mirror but opposite sign, so that the spherical aberration of the mirror was eliminated when the mirror was tested at its centre of curvature. The resultant image should have zero spherical aberration. However, the null corrector itself was not assembled correctly [9]. As a result, the primary mirror was made to incorrect form.

HST was repaired by inserting a corrective optics system, Corrective Optics Space Telescope Axial Replacement (COSTAR), from the space shuttle Endeavor in December 1993. COSTAR consists of five sets of two-mirror correctors for the five instruments [7]. Some of the mirrors were tested by two independent interferometers, a computer-generated hologram (CGH) interferometer and a partial null interferometer, during the fabrication. The wavefront error of $\lambda/8$ in p-v on each Zernike term and $\lambda/100$ in rms at 632.8nm were achieved [10].

This historic event teaches us the importance of optical testing. If the mirror had been properly tested and double checked by at least two independent testing methods, such a disaster would not have happened.

V. TESTING METHODS FOR ASPHERIC OPTICS

Highly aspheric optics have a feature that the edge goes up or down steeply compared with a sphere which osculates on the vertex of the asphere. Therefore, the height difference between the aspherics and the sphere goes larger on the edge than inner part of the optics.

In case of using interferometry for measuring aspheric optics, a fringe is generated on the place where every one wavelength in optical path difference occurs. As the edge of aspherics gives large height difference, the fringes in the edge would be generated close to each other. This would make it difficult or impossible to identify the fringes individually by eye or imaging device [11].

A sample analysis of the height difference was undertaken for the Gemini telescopes. If the image of the mirror was captured by an imaging device which has 512×512 pixels and filled into the pixels in full, 1 pixel size is equivalent to 15.625mm on the diameter of the mirror. The height difference of the mirror from a spherical surface was calculated for 1 pixel distance along the radius. The number of fringes for one pixel was counted from the height difference. One wavelength was assumed to be 632.8nm, the wavelength of a He-Ne laser.

The analysis results are listed in Table 2. In the centre of the mirror, the number of fringes was small enough to detect the individual fringes. However, at the edge of the mirror, 67 fringes should be accommodated in one pixel. Consequently, the fringes could not be detected individually.

TABLE 2. Number of fringes on each pixel when the Gemini primary mirror is tested by an interferometer and imaged on a 512×512 pixelled imaging device. 1 wave = 632.8nm.

(a) Edge part of the mirror.

Pixel number	Radius [mm]	Height [mm]	Height [mm] (Sph. Mirror)	Difference [waves]	Fringes [# / pixel]
512	4000.000	277.7727	279.1304	2145.5	67
511	3984.375	275.6069	276.9434	2112.1	66
510	3968.750	273.4496	274.7651	2079.0	65
509	3953.125	271.3007	272.5956	2046.3	65
508	3937.500	269.1603	270.4347	2014.0	

(b) Central part of the mirror.

Pixel number	Radius [mm]	Height [mm]	Height [mm] (Sph. Mirror)	Difference [waves]	Fringes [# / pixel]
294	593.750	6.120467	6.121120	1.03	1/6
288	500.000	4.340277	4.340605	0.52	1/32
257	15.625	0.004239	0.004239	0.00	
256	0.000	0.000000	0.000000	0.00	zero point
255	-15.625	0.004239	0.004239	0.00	

To overcome the difficulties of measuring aspheric optics by using interferometry, several attempts have been made. They are use of combinations of null optics, increased number of pixels on CCD camera or other detector arrays, longer wavelengths, two-wavelength techniques, etc.

Using a null corrector in testing aspheric optics is a frequently employed method. In testing the primary mirror of HST, a null corrector was used [9]. However, null optics is often very difficult and expensive to produce [12] and the null optics itself must be verified.

Computer Generated Hologram (CGH) together with Phase Shifting Interferometer has been used for aspheric optics. Burge [13] developed the CGH test method for testing large convex aspheres. The CGH was claimed to measure aspheric convex mirrors up to the diameter of 1.15m with the accuracy of 4nm in rms surface measurement. This method was used in testing the secondary mirrors of Multi-Mirror Telescope and COSTAR for HST [10].

Greivenkamp [14] modified phase-shifting interferometry, which is called Sub-Nyquist interferometry (SNI). SNI used sparse-array sensors and improved the measurements over 2 orders of magnitude. However, there were several assumptions underlying the measurements, which increase the testing errors.

Kwon *et al.* [15] used longer wavelength Twyman-Green interferometer for an aspheric mirror. The mirror was an off-axis parabolic collimator mirror with effective aperture of 1.22m, whose height difference from the best fit sphere was 260.6μm. A CO_2 laser of 10.6μm was employed for the test and $\lambda/4$ peak-to-valley surface error appeared.

Cheng and Wyant [16] and Creath *et al.* [17] applied two-wavelength phase-shifting interferometry for aspheric optics. The surface accuracy was assumed to be $\lambda_{eq}/100$ in rms from the phase-shifting techniques, where $\lambda_{eq} = \lambda_1\lambda_2/|\lambda_1 - \lambda_2|$. When the two wavelengths of 0.6328μm by He-Ne laser and 0.4880μm by argon-ion laser were used, the surface accuracy was expected to be 0.021μm in rms.

Melozzi et al. [18] developed Multiple Annular Interferograms (MAI) technique. An aspheric mirrors of 288mm in ROC, 114mm in diameter, and 12.7λ (1λ=0.6328μm) in the height difference from the best fit sphere was tested by MAI. Overall accuracy was estimated to $\lambda/4$ in p-v wavefront error.

Profilometry has also been used for measuring the profile of aspheric optics. Dil *et al.* [19] developed a profilometer with the precision of ±5nm by using contacting probes and an optical differential technique. Burge [13] made a swing arm profilometer for testing large convex aspheres. The profilometer achieved 50nm of rms measurement accuracy over 1.8m mirrors.

Though the above techniques have increased the available measuring range, there are still restrictions in actual application such as high cost of the instrument, long lead times in the design of the test, difficulty of calibration, and decrease in the precision of the test [14]. As for large optics, size of available space is another restriction for testing methods.

Considering the restrictions, the Foucault test is one of the best testing methods for large aspheric optics as it is simple and easy to test and to diagnose the result, and it costs little. Taking advantages of the Foucault test, I [20] developed Automated Quantitative Knife-Edge Test (AQuaKET). AQuaKET has a capability of testing highly aspheric mirrors without using a null corrector and achieved the accuracy of $\lambda/20$ in peak-to-valley and $\lambda/100$ in rms wavefront which is accurate enough for testing large aspheric mirrors.

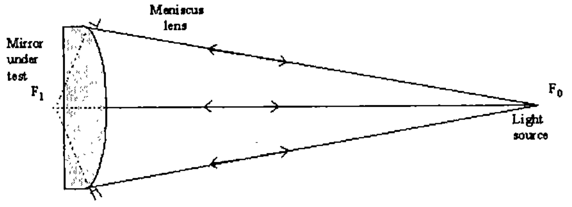

FIG. 3. Schematic representation of a convex mirror test by using a meniscus lens.

VI. TESTING LARGE ASPHERIC CONVEX MIRROR

A convex mirror diverges rays when they came from a point source and reflected on the mirror surface. In order to make the diverging light converge, extra optics or other devices should be employed to test methods. Hindle type tests [21] use a spherical mirror (and collimator) as null optics. Xiang *et al.* [22] developed a birefringent common-path interferometer and tested a convex spherical surface of 200mm in diameter. Burge [23] developed a CGH test method and a swing arm profilometer for testing large convex aspheres.

Another way of converging the rays is using a meniscus lens as a modified Hindle test [21]. Fig. 3 illustrates the use of a meniscus lens for convex mirror testing. The rays coming from a light source (F_0) go through the meniscus lens, reflect on the mirror, bound back at the meniscus lens and return to F_0. Therefore, a testing method can be applied to this set-up.

Large telescopes need large convex mirrors as secondaries. If the convex mirrors are to be tested by using a meniscus lens, the lens should be larger in diameter than the mirror under test. The f/6 secondary mirrors of the Gemini telescopes are designed to be 2.4m in diameter. However, there is no meniscus lens larger than 2.4m in the world. At present, the largest meniscus lens in the world is 1.5m in diameter. Producing a larger meniscus lens would cost much, probably more than the cost of the secondary mirror itself.

One solution suggested was to employ a small aperture meniscus lens and to overlap the patches, which is called modified sub-aperture Hindle test [24]. In order to validate the test method, a testing tower was built for smaller mirror and meniscus lens. The set-up has been simulated by ray-tracing software to achieve the best image quality. Table 3 shows the specification of the test set-up, and the resultant image size was checked to find out whether the image size is small enough to be able to test a larger mirror. The resultant image size by simulation was 0.05mm, which looks good enough to test convex mirrors in large telescopes. AQuaKET, combined with the set-up, can perform the testing of large telescopes with highly aspheric mirrors.

TABLE 3. Specification of the set-up for testing a convex mirror. unit [mm]

Surface	ROC	Diameter from F_0	Distance	Remarks
Meniscus upper	2832	1080	2165	BK7
meniscus lower	2756	1080	2241	
Mirror	3727	830	3605	cc -2.86391

VII. CONCLUSIONS

Space telescopes and ground-based large telescopes are usually composed of aspheric optical mirrors. As the overall science and technology advance, higher accuracy is required in optics as well. However, there are few optical testing methods which can achieve the specification for aspheric optics. Moreover testing aspheric convex mirrors with large apertures becomes harder as it requires special optical components and testing methods.

I have developed a testing method (AQuaKET) by renovating an old testing method [20]. AQuaKET has the capability of testing aspheric optics, meeting the required accuracy of a large telescope. Furthermore, a method of testing large convex mirrors is developed and suggested.

In general, optical devices have combinations of many spherical lenses and mirrors in order to enhance the optical quality. The number of the optical components can be reduced considerably by using aspheric optics.

When production of aspheric optics become easier and a useful testing method appears, spherical optics can be replaced by fewer aspheric optics. This would be critical for space optics, where smaller and lighter instruments are pursued. Aspheric optics will also benefit hand-held devices.

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